Determination of the pole mass at D0

- (Introduction)
- Inclusive cross section & extraction
- Differential cross section & extraction
- Conclusions

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American Physical Society –
Division of Particle & Fields

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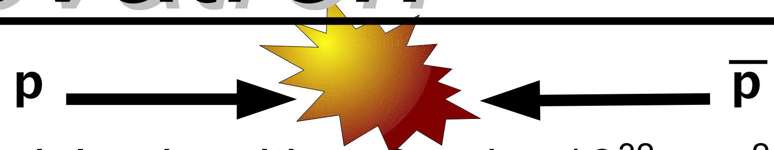
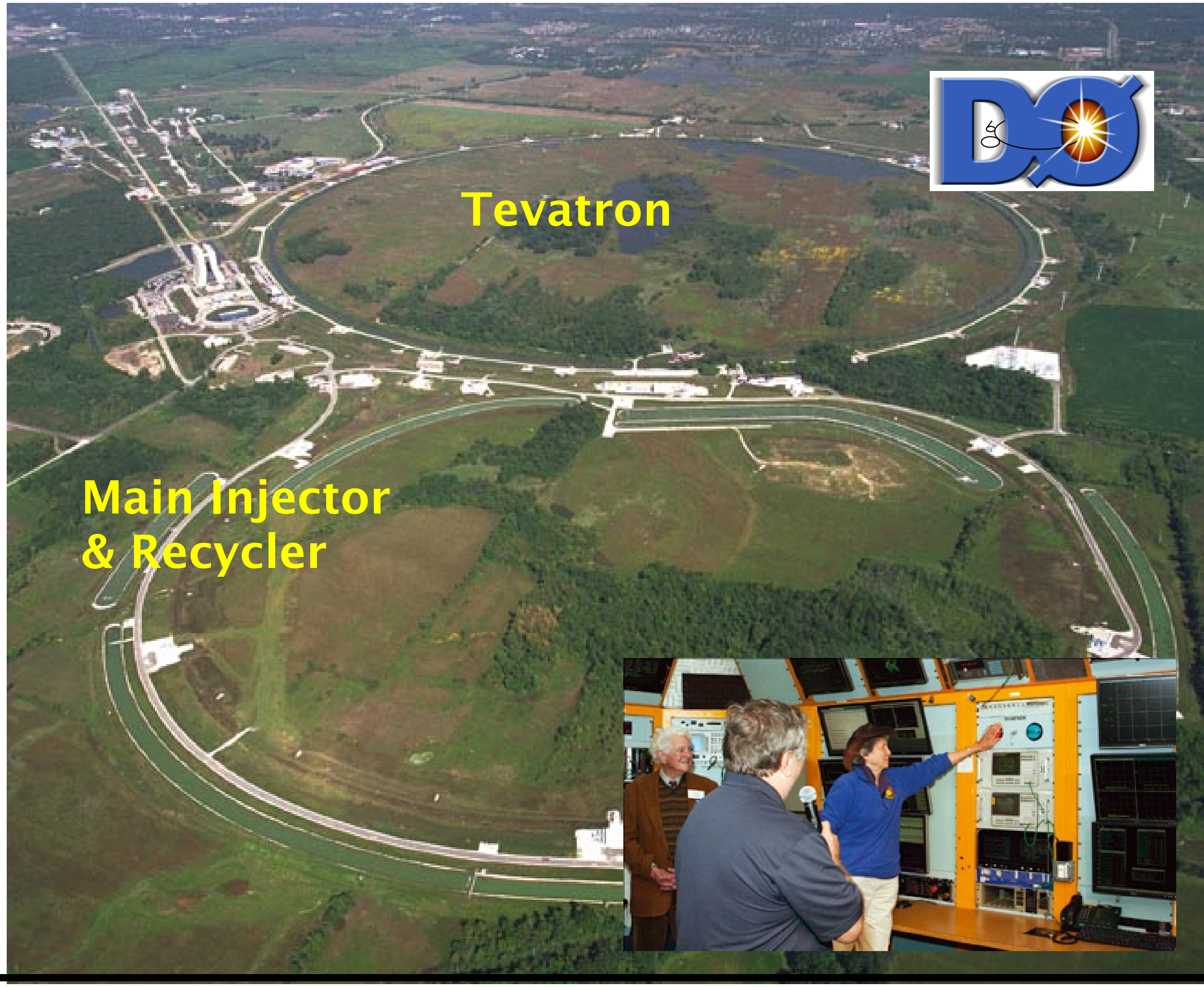
The Tevatron



$\sqrt{s}$=1.96 TeV

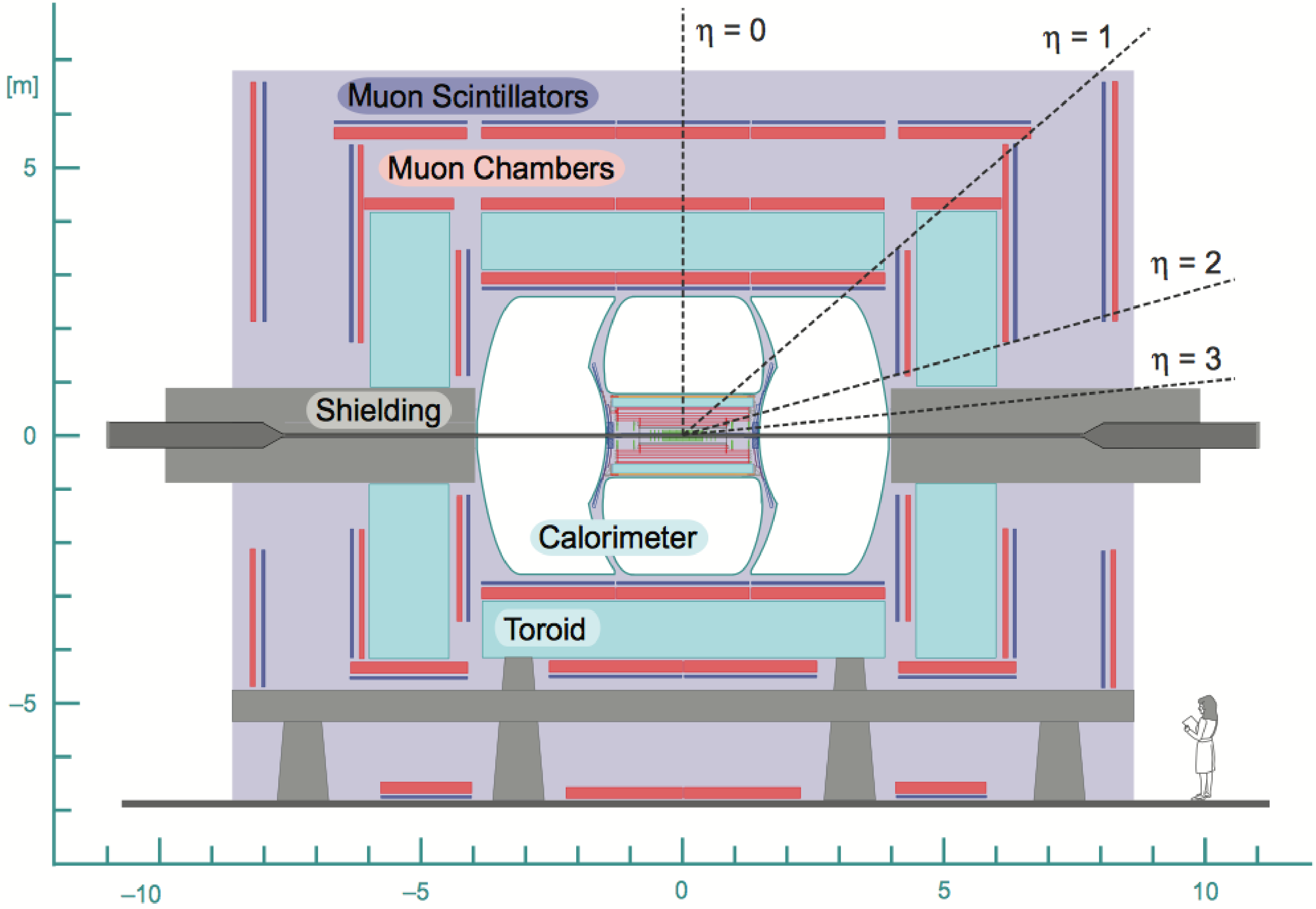
- Peak luminosities: 3 – 4 x 10^{32} $cm^{-2}s^{-1}$
- ~10 fb^{-1}/experiment recorded
- Tevatron shutdown September 2011



D0 detector

General purpose 4π detectors:

- **Tracker**: Detection and momentum measurement for charged particles
- **Calorimeter**: Identification and energy measurement of jets and electrons
- **Muon system**: Identification and momentum measurement of muons



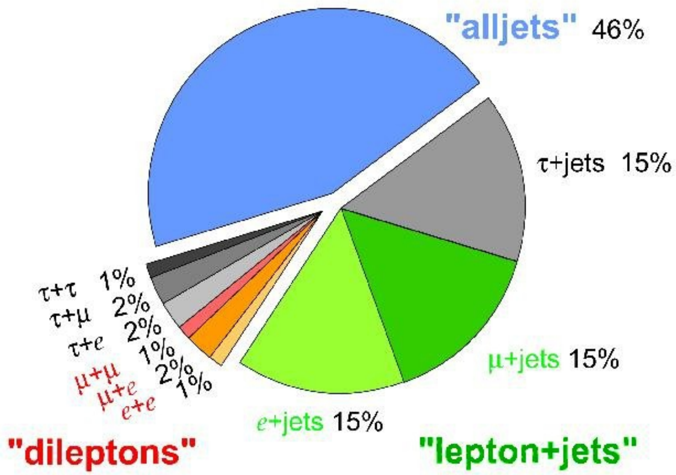
Top quark – introduction

- Top is the heaviest fundamental particle discovered so far
  → $\boldsymbol{m_t}$ **= 173.34 ± 0.76 GeV**
  [arxiv:1403.4427]

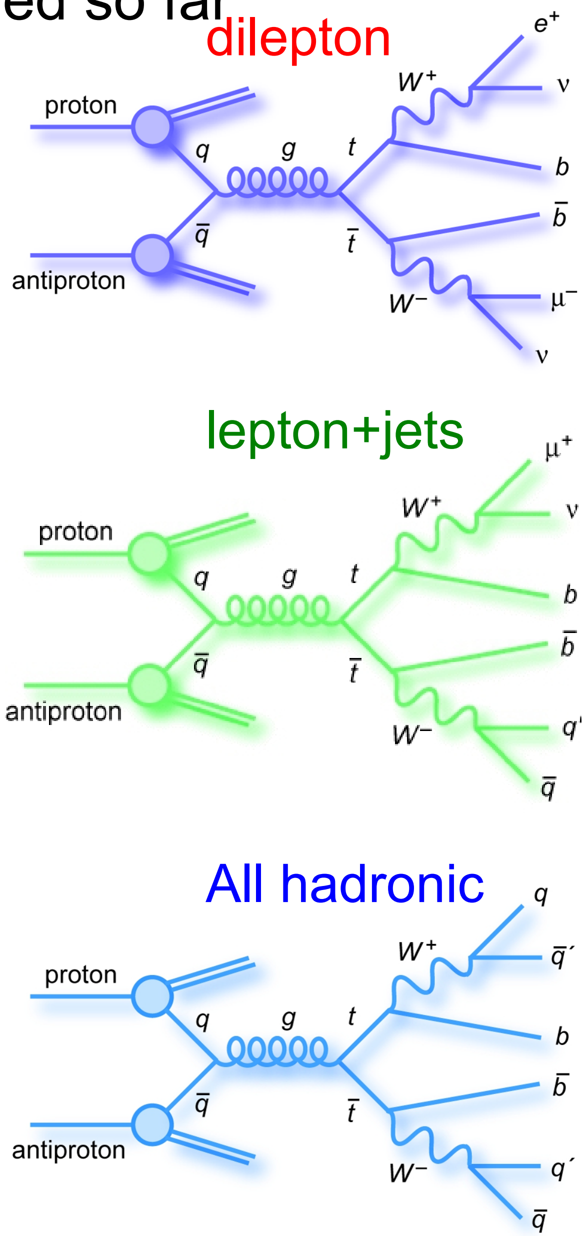
- Lifetime: $\tau \sim 5\mathrm{x}10^{-25}$ s, $\tau < 1/\Lambda_{QCD} << m_t/\Lambda^2_{QCD}$
  (indirect)
  → **Observe bare quark properties**

- Large Yukawa coupling to Higgs boson
  → $\lambda_t \sim 1$ **only $\boldsymbol{m_t}$ is natural mass**
  Special role in electroweak symmetry breaking ?

Top Pair Branching Fractions



BR, bg increase



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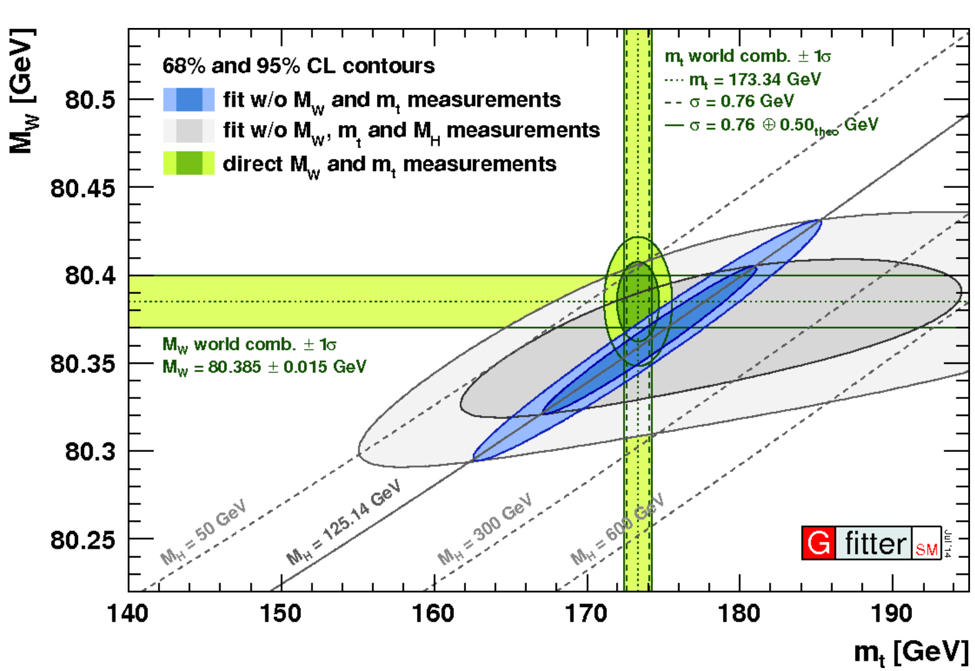
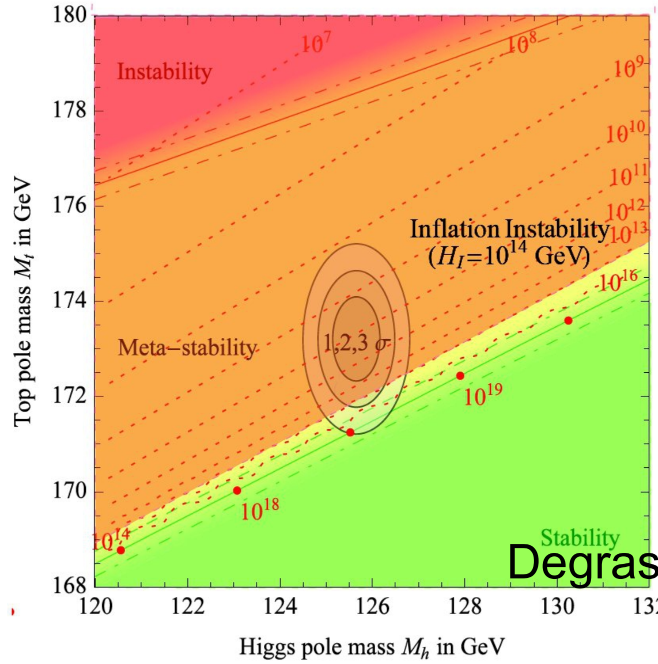
Top quark mass





Degrassi et al.

- Self-consistency test of the SM & stability of the EW vacuum both rely/use pole mass – method dependent
  - **Indirect extraction** from e.g. cross section, end point, J/psi method
    → top quark pole mass
  - **Direct methods** e.g. template, matrix element, likelihood, ideogram
    → “MC” mass, close to pole mass

Caveat:

- “MC” mass different from the pole mass
- Estimates: O(0.5 GeV) difference to pole mass

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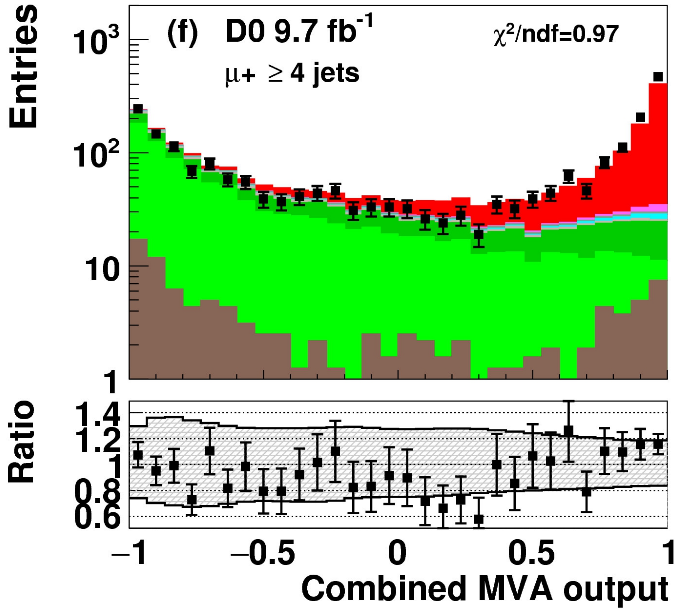
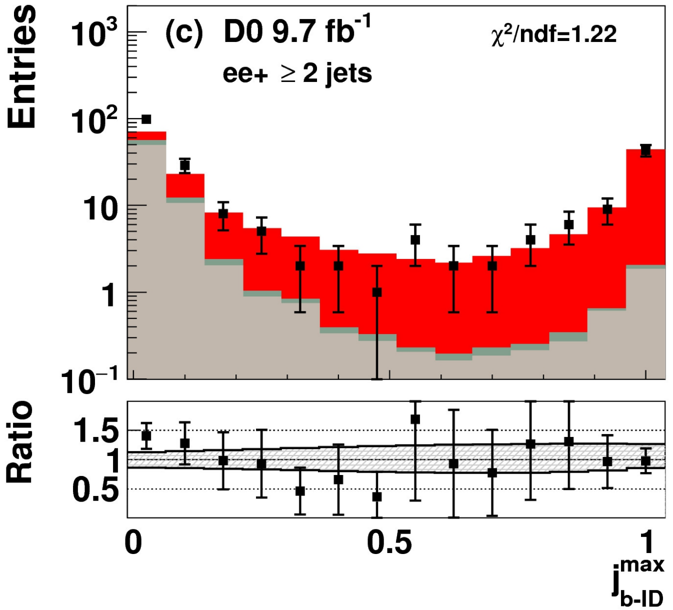
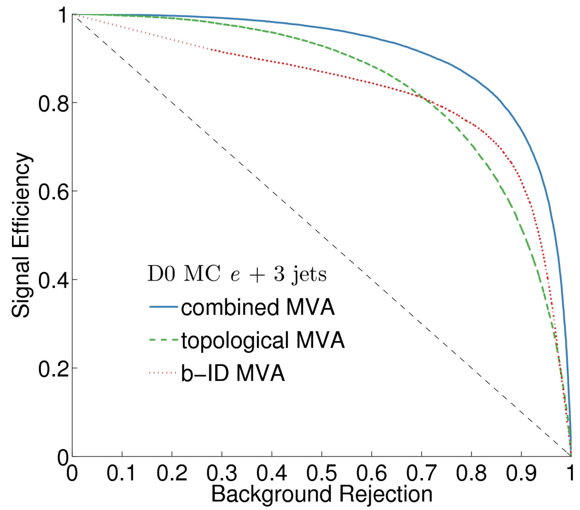
Inclusive cross section

- Simultaneous measurement of the ttbar cross section in the l+jets and dilepton channel
  - Combined MVA discriminant, using nuisance parameters
  - Separated by lepton flavor and #jets
- Optimized for <u>smallest uncertainty of extracted top quark pole mass</u>







Phys. Rev. D 94, 092004 (2016)

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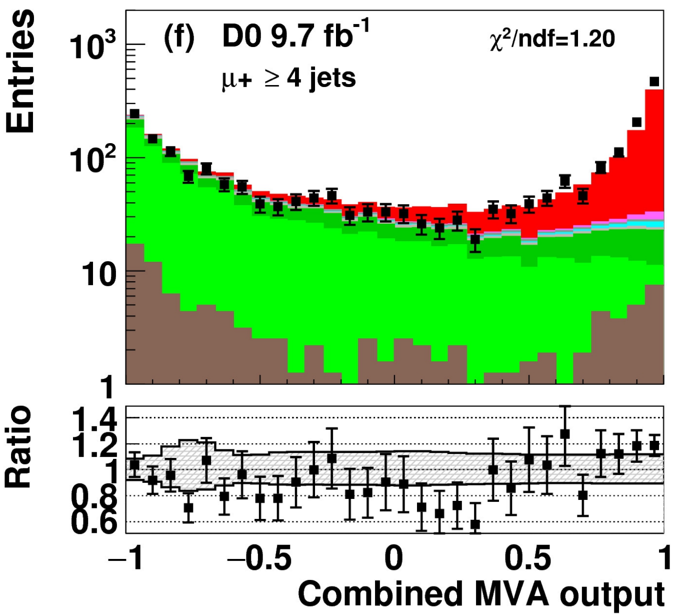
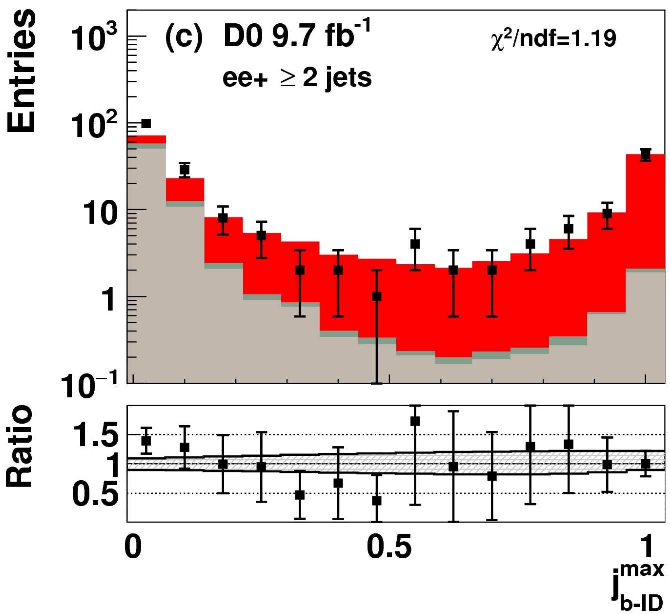
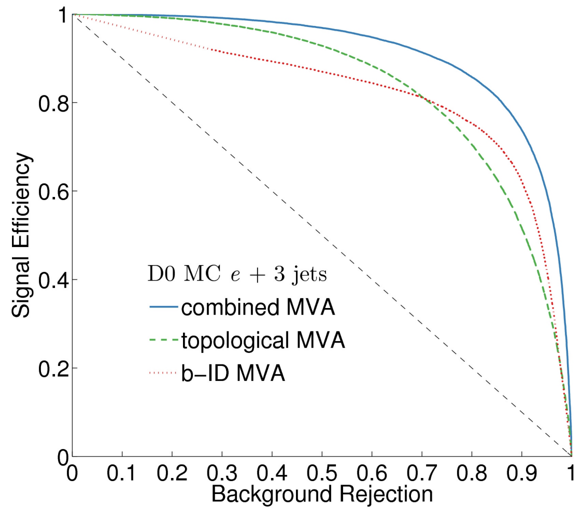






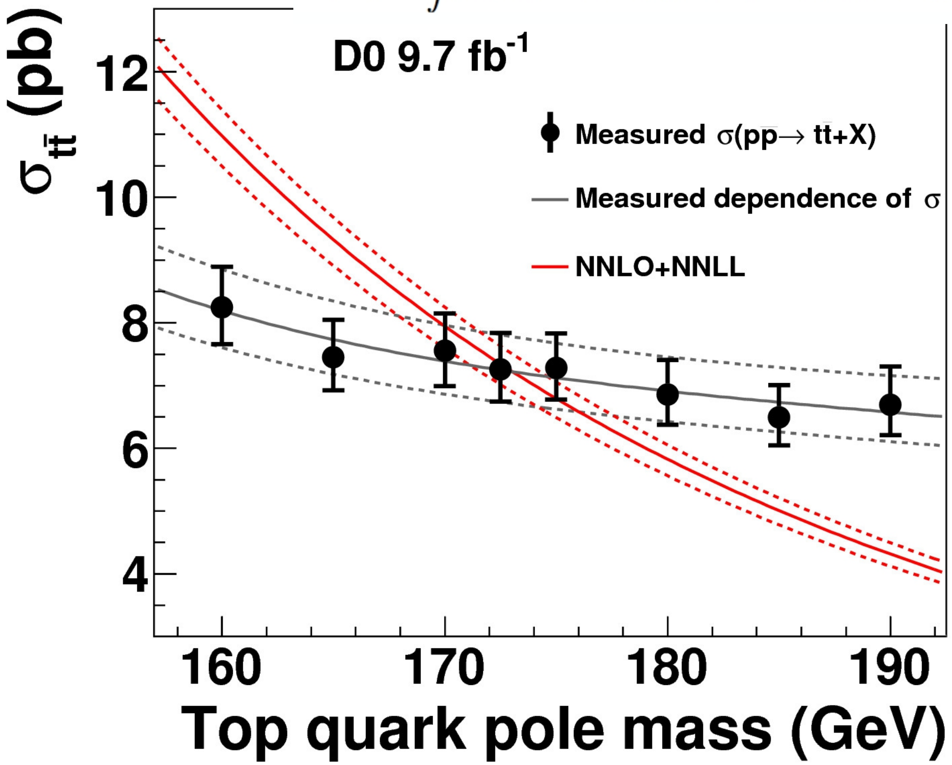
Phys. Rev. D 94, 092004 (2016)

σ_{tot} = 7.26 ± 0.12 (stat.) ± 0.54 (syst.) pb   δs/s = 7.6%

Inclusive cross section

- Repeat experimental measurement procedure for every mass point
  - Systematic uncertainties taken at each mass point, except signal model (scaled from the 172.5 GeV case)
- Characterize slope by 4th order polynomial, use likelihood approach and compare with NNLO+NNLL predictions by top++ (Czakon et al.)
- Maximum of normalized combined likelihood function: $L(m_t) = \int f_{\text{exp}}(\sigma|m_t)\ [f_{\text{scale}}(\sigma|m_t) \otimes f_{\text{PDF}}(\sigma|m_t)]\ d\sigma$

Top quark mass [GeV]	Cross section $\sigma(t\bar{t})$ [pb]
150	$9.70 \pm 0.16\,(\text{stat.})^{+0.73}_{-0.67}\,(\text{syst.})$
160	$8.25 \pm 0.14\,(\text{stat.})^{+0.63}_{-0.57}\,(\text{syst.})$
165	$7.46 \pm 0.13\,(\text{stat.})^{+0.58}_{-0.51}\,(\text{syst.})$
170	$7.55 \pm 0.13\,(\text{stat.})^{+0.58}_{-0.55}\,(\text{syst.})$
172.5	$7.26 \pm 0.12\,(\text{stat.})^{+0.57}_{-0.50}\,(\text{syst.})$
175	$7.28 \pm 0.12\,(\text{stat.})^{+0.54}_{-0.49}\,(\text{syst.})$
180	$6.86 \pm 0.12\,(\text{stat.})^{+0.53}_{-0.47}\,(\text{syst.})$
185	$6.50 \pm 0.11\,(\text{stat.})^{+0.50}_{-0.43}\,(\text{syst.})$
190	$6.70 \pm 0.11\,(\text{stat.})^{+0.60}_{-0.47}\,(\text{syst.})$

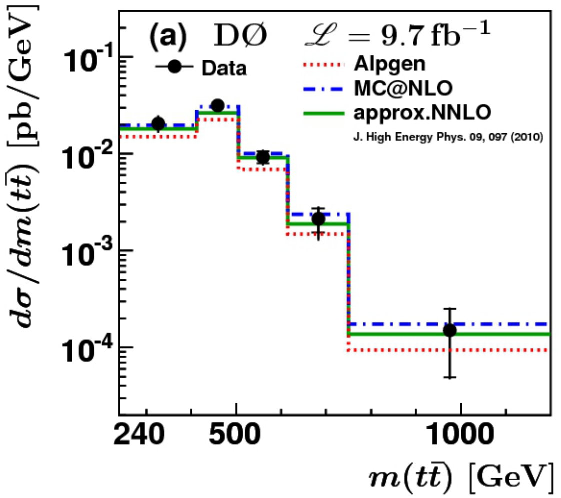


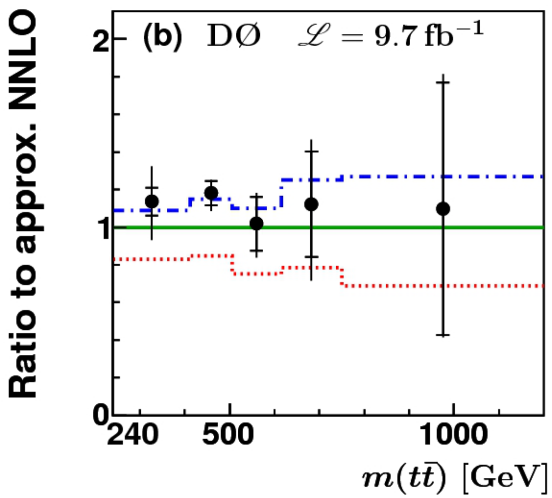
Phys. Rev. D 94, 092004 (2016)

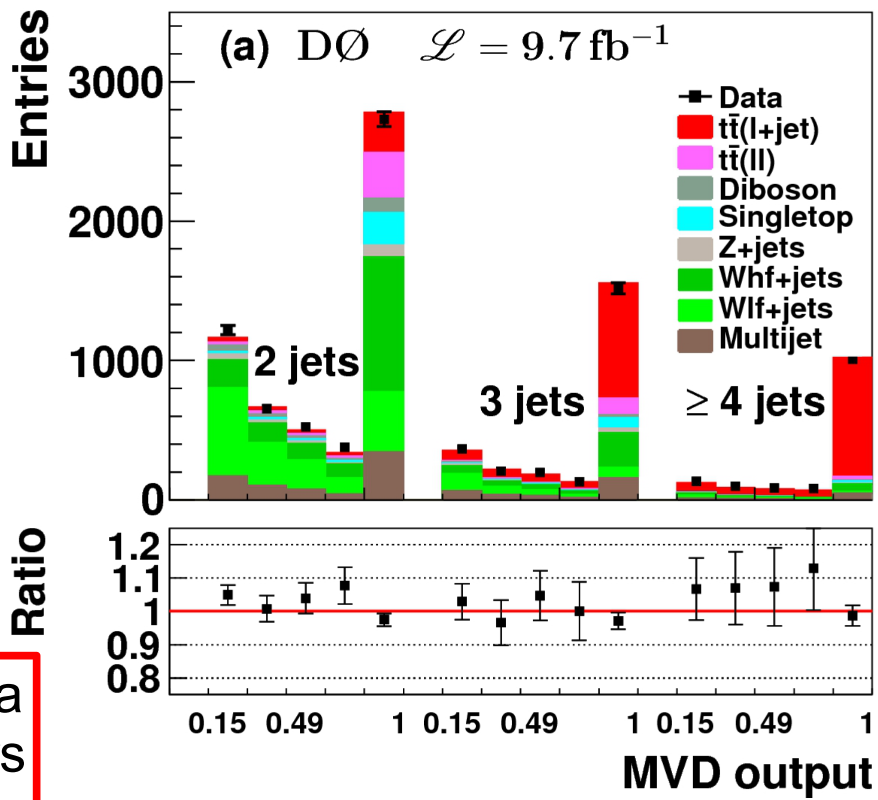
$m_t = 172.8 \pm 1.1$ (theo) ± 3.2 (exp) GeV $\qquad \delta m_t/m_t = 1.9\%$

Differential cross sections

- Measured in the l+jets channel, using full D0 data set
- Employ a MVA discriminant to determine sample composition
  (W+light quark jets vs. W+heavy quark jets vs. ttbar)
- Top quarks reconstructed by kinematic fit (chi2 based), best permutation used
- Uses regularized matrix unfolding to correct for detector effects & acceptance





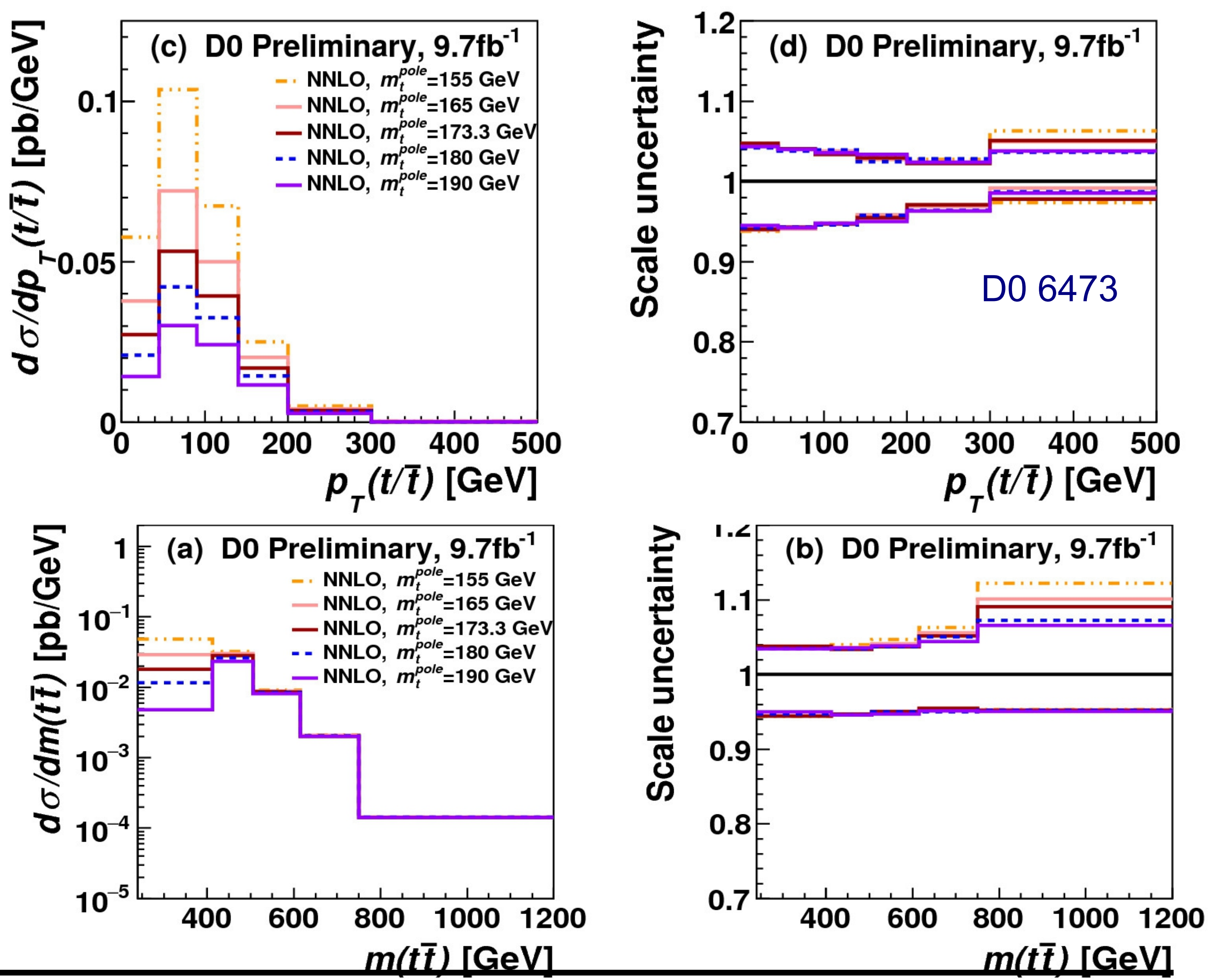


Phys. Rev. D 90, 092006 (2014)

- Typical precision is about 4-5% in bulk of the data
- Full covariance matrix provided for model builders
- Constrains low mass axi-gluons

Predictions & Uncertainties (NNLO)

- Shows selected set of predictions and scale uncertainties
- Sensitive in ttbar mass threshold region and 1st to 4th bin of pT(t/tbar)



Theoretical uncertainties

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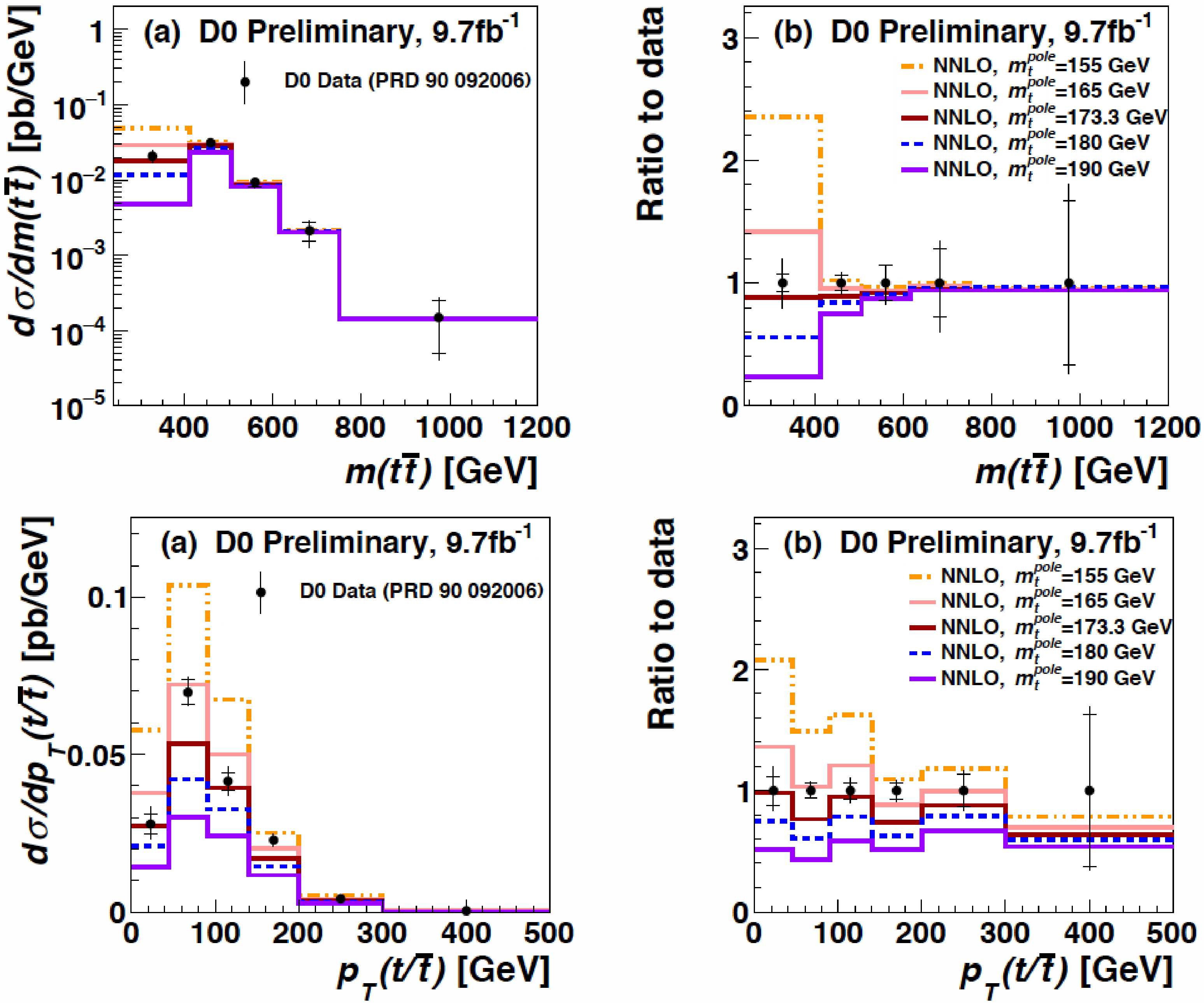
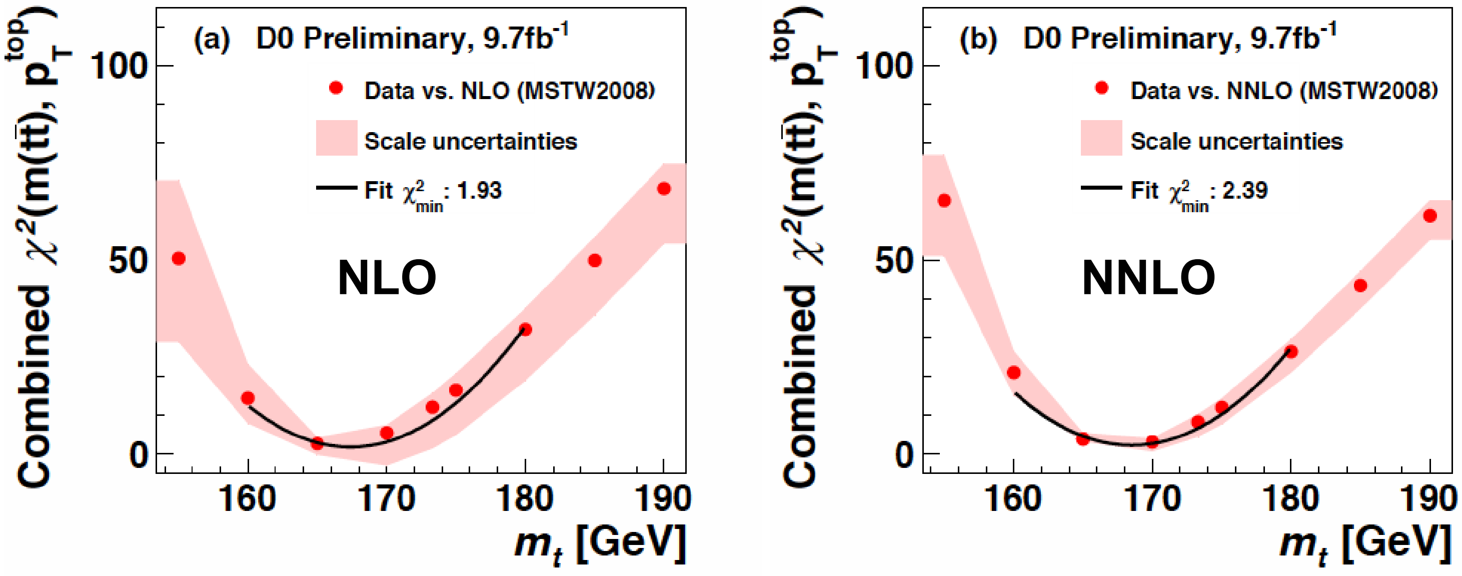
- Shows selected set of predictions and D0 data
- Sensitive in ttbar mass threshold region and 1st to 4th bin of pT(t/tbar)



Selected results

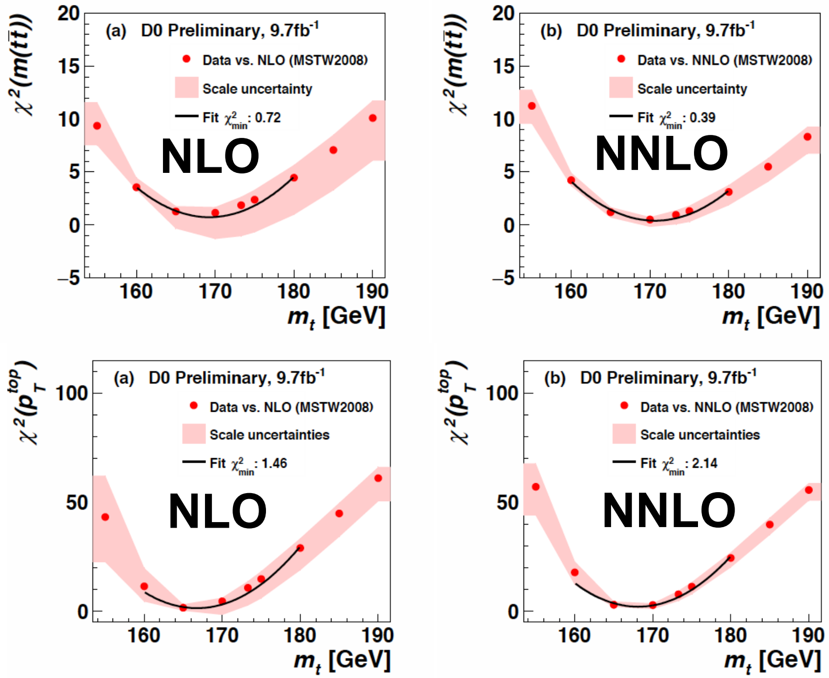
- As an example shown for MSTW2008NNLO
- NNPDF, CT10, HERAPDF1.5 as well
- NLO and NNLO



- Derive a chi2 per mass hypothesis
  - Includes the correlations of statistical uncertainty due to the use of reg. MU

$$\chi^2 = \sum_{i,j} (x_i^{\text{true}} - x_i^{\text{theo}}) \cdot \mathbf{V}^{-1}_{\mathbf{xx};\ \mathbf{i,j}} \cdot (x_j^{\text{true}} - x_j^{\text{theo}})$$

- Minimum of parabola is preferred top mass
  - Delta chi2 = 1 yields uncertainty
- Combination of pT & mTT uses correlations in MC@NLO between those to derive combined chi2 → top mass via same approach



Individual results

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Order & PDF	$m(t\bar{t})$	m_t^{pole} [GeV] p_T^{top}	$m(t\bar{t}) \oplus p_T^{\text{top}}$
NLO:			
MSTW2008	169.3 ± 5.7	166.8 ± 2.9	167.4 ± 2.5
CT10	169.4 ± 5.9	167.9 ± 3.0	167.5 ± 2.6
NNPDF2.3	169.0 ± 6.0	166.4 ± 2.9	167.1 ± 2.5
HERAPDF1.5	167.2 ± 6.4	166.0 ± 2.9	165.1 ± 2.7
NNLO:			
MSTW2008	170.7 ± 5.6	168.0 ± 2.5	168.5 ± 2.3
CT10	171.5 ± 5.5	169.4 ± 2.4	169.7 ± 2.2
NNPDF2.3	171.1 ± 5.6	168.5 ± 2.5	169.0 ± 2.3
HERAPDF1.5	172.6 ± 5.6	170.3 ± 2.6	170.2 ± 2.3

TABLE II. Extracted top quark pole mass at NLO and at NNLO pQCD employing the absolute differential cross section as a function of $m(t\bar{t})$ or p_T^{top} and its combination for the MSTW2008, CT10, NNPDF2.3, and HERAPDF1.5 PDF.

- Average top quark mass following this approach:
  - Use only the three global PDFs (MSTW2008, CT10, NNPDF23)
  - Follow PDF4LHC: PDF uncertainty is max difference added in quadrature
  - Using HERA results in a shift of -0.5 at NLO and +0.3 at NNLO, similar uncertainties...shifts due to different xsec prediction when using HERA

Combined results

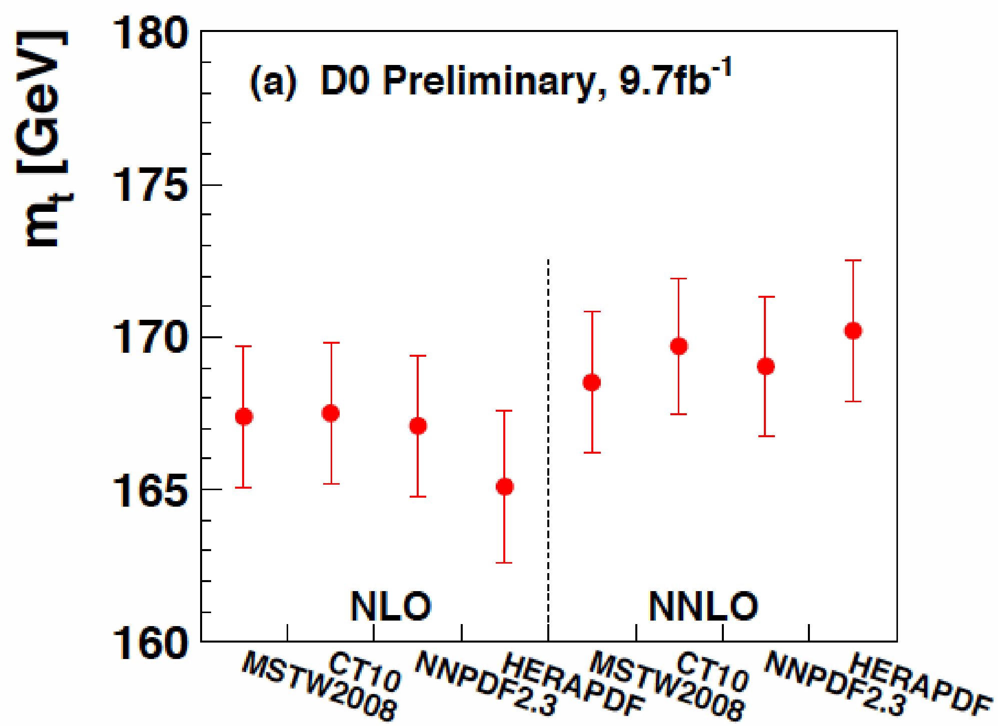
Order & PDF	$m_t^{\text{pole}} \pm \delta_{\text{tot.}}$ [GeV] $m(t\bar{t}) \oplus p_T^{\text{top}}$	δ_{exp} [GeV] $m(t\bar{t}) \oplus p_T^{\text{top}}$	$\delta_{\text{theo}}^{\text{scale}}$ [GeV] $m(t\bar{t}) \oplus p_T^{\text{top}}$
NLO			
MSTW2008	167.4 ± 2.5	± 2.0	± 1.5
CT10	167.5 ± 2.6	± 2.0	± 1.6
NNPDF2.3	167.1 ± 2.5	± 2.0	± 1.5
HERAPDF1.5	165.1 ± 2.7	± 2.3	± 1.5
NNLO			
MSTW2008	168.5 ± 2.3	± 2.2	± 0.7
CT10	169.7 ± 2.2	± 2.0	± 0.9
NNPDF2.3	169.0 ± 2.3	± 2.1	± 0.8
HERAPDF1.5	170.2 ± 2.3	± 2.2	± 0.7

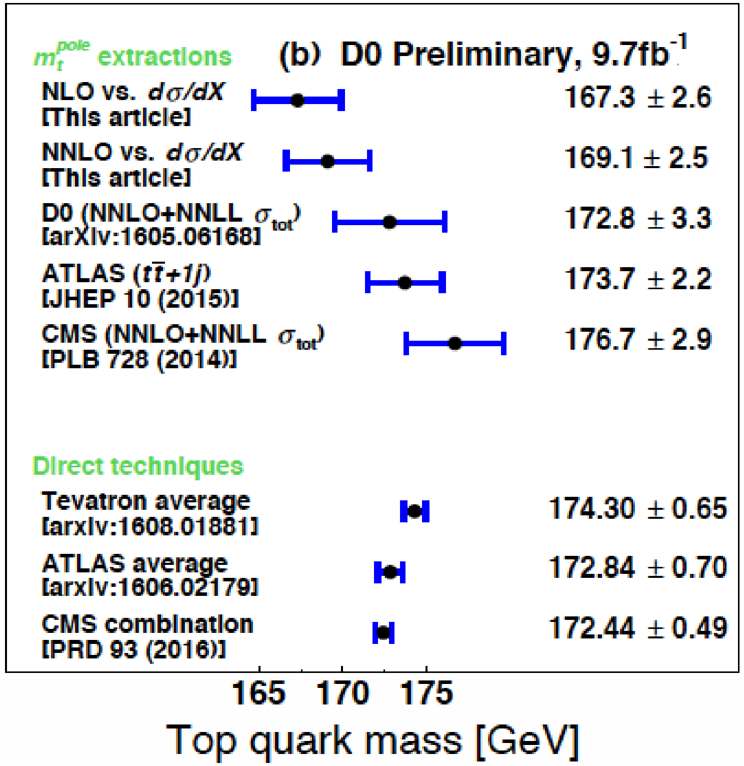
TABLE III. Extracted m_t^{pole} at NLO and at NNLO employing the combined χ^2 in $m(t\bar{t})$ and p_T^{top} distributions for the MSTW2008, CT10, NNPDF2.3, and HERAPDF1.5 PDF. The special setting to separately determine the theoretical uncertainty (for details see text) neglects the correlations between the bins of a measured distribution.

- Showing only the combined mass results and breakdown in uncertainty due to experimental sources and theoretical
- NNLO scale uncertainties smaller by a factor of 2 compared to NLO

Results & comparisons

- Consistent amongst all the PDFs & **able to compete with LHC results**





$m_t = 169.1 \pm 2.2\ (\text{exp}) \pm 0.8\ (\text{scale}) \pm 1.2\ (\text{PDF})$ GeV

$\delta m_t/m_t = 1.5\%$

Summary

- Extractions of the top quark mass from cross sections
  - Inclusive extraction, most precise at Tevatron

$\boxed{m_t = 172.8 \pm 1.1 \text{ (theo)} \pm 3.2 \text{ (exp) GeV} \qquad \delta m_t/m_t = 1.9\%}$

  - Differential extraction, additional improvement by 25%

$\boxed{m_t = 169.1 \pm 2.2 \text{ (exp)} \pm 0.8 \text{ (scale)} \pm 1.2 \text{ (PDF) GeV} \qquad \delta m_t/m_t = 1.5\%}$

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- Ongoing work for combination, needs detailed study of correlations

Thank you!

D0 Top Web pages

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